QCD Physics with MIPP

Rajendran Raja

Presentation to the QCD at Tevatron Workshop

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Brief Description of Experiment

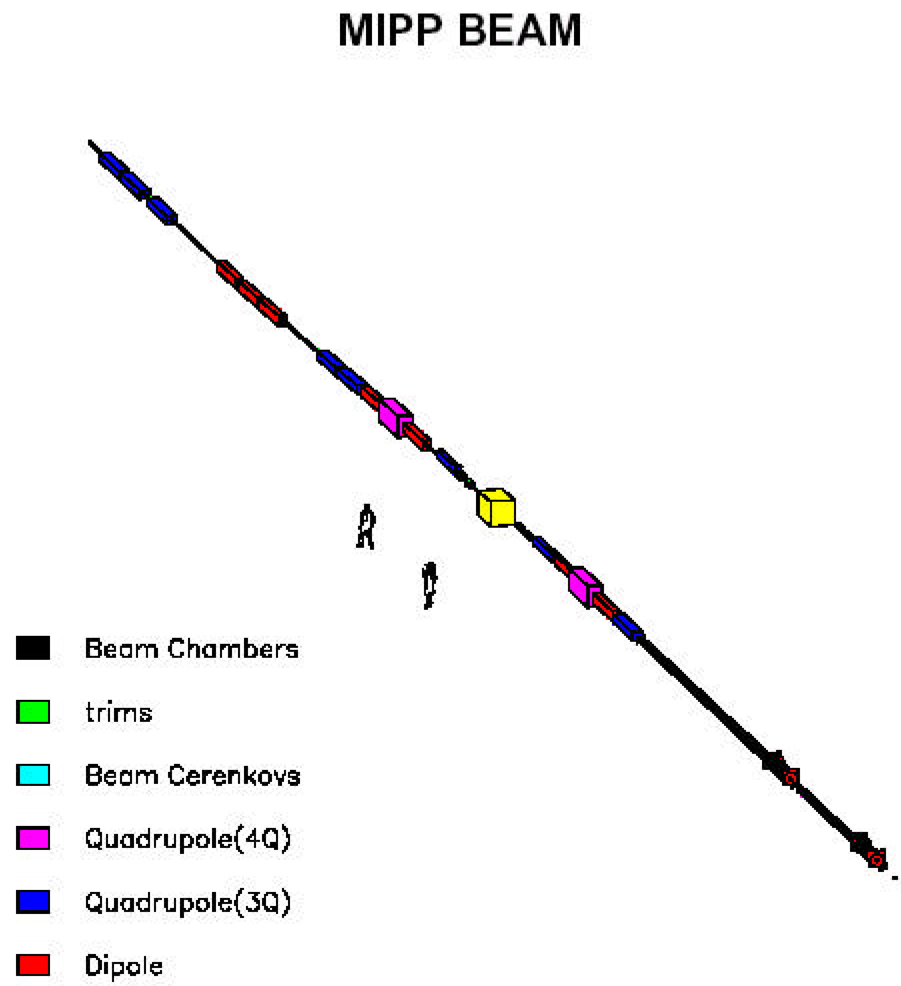
- Approved November 2001
- Situated in Meson Center 7
- Uses 120GeV Main Injector Primary protons to produce secondary beams of $\pi^{\pm}$ $K^{\pm}$ $p^{\pm}$ from 5 GeV/c to 100 GeV/c to measure particle production cross sections of various nuclei including hydrogen.
- Using a TPC we measure momenta of ~all charged particles produced in the interaction and identify the charged particles in the final state using a combination of dE/dx, ToF, differential Cherenkov and RICH technologies.
- Open Geometry- Lower systematics. TPC gives high statistics. Existing data poor quality.

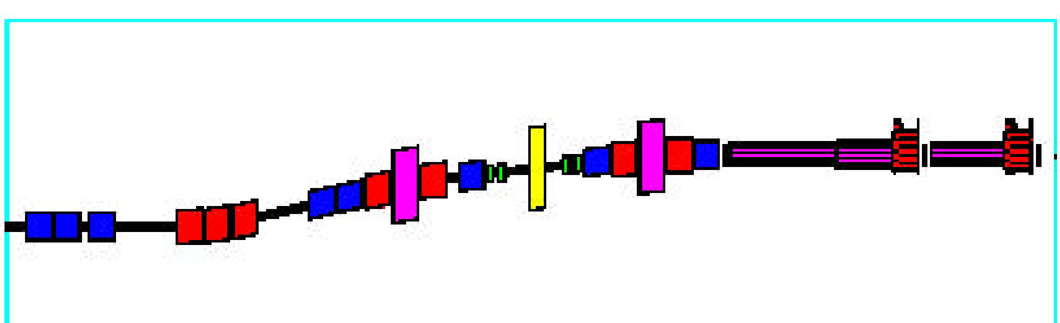
Physics Interest

- Particle Physics-To acquire unbiased high statistics data with complete particle id coverage for hadron interactions.
  - » Study non-perturbative QCD hadron dynamics, scaling laws of particle production
  - » Investigate light meson spectroscopy, pentaquarks, glueballs
- Nuclear Physics
  - » Investigate strangeness production in nuclei- RHIC connection
  - » Nuclear scaling
  - » Propagation of flavor through nuclei
- Service Measurements
  - » Atmospheric neutrinos – Cross sections of protons and pions on Nitrogen from 5 GeV- 120 GeV
  - » Improve shower models in MARS, Geant4
  - » Make measurements of production of pions for neutrino factory/muon collider targets
  - » Proton Radiography– Stockpile Stewardship- National Security
  - » MINOS target measurements – pion production measurements to control the near/far systematics
- HARP at CERN went from 2-15GeV incoming pion and proton beams. MIPP will go from 5-100 GeV/c for 6 beam species $\pi^{\pm}$ $K^{\pm}$ $p^{\pm}$

MIPP Secondary Beam

- Installed in 2003. Delivering slow spill commissioning beam (40GeV/c positives since February 2004). Sonn will increase rep rate once we commission the detector.

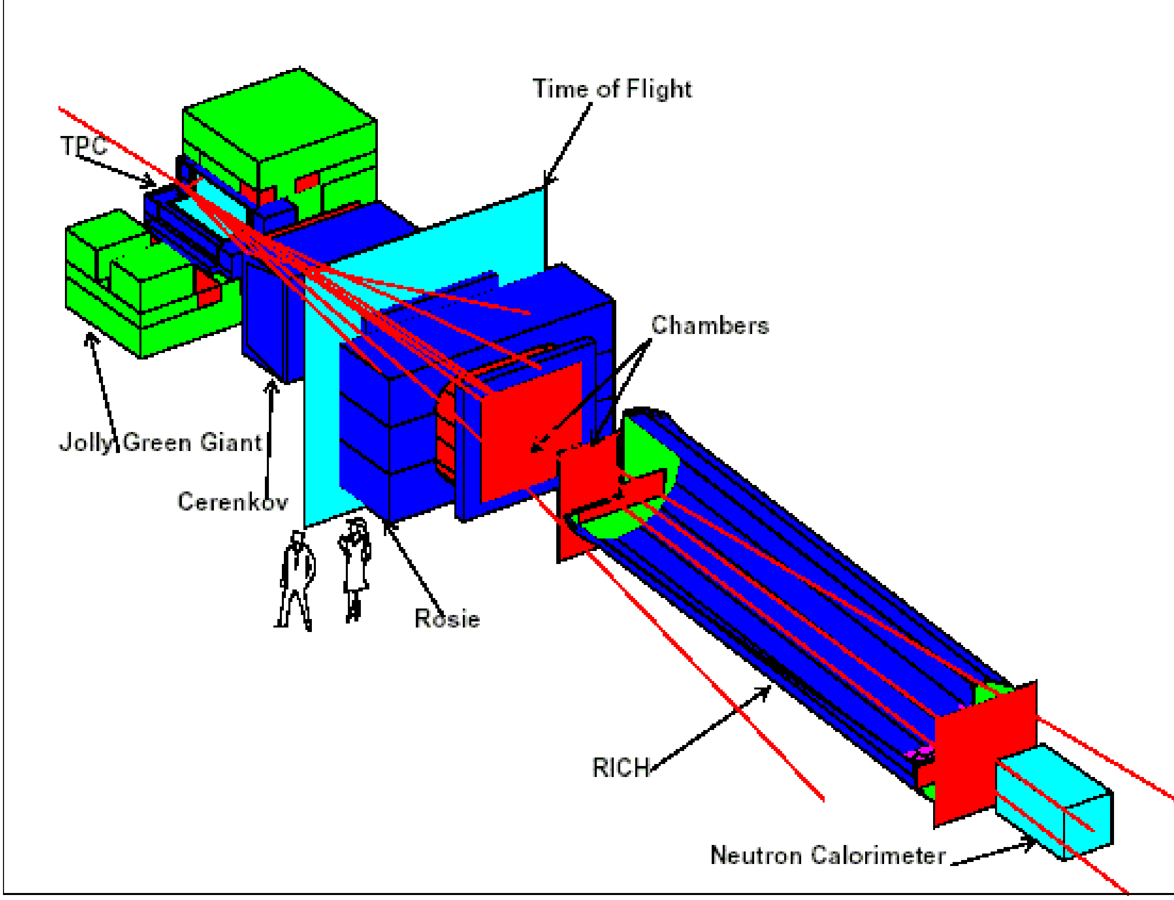


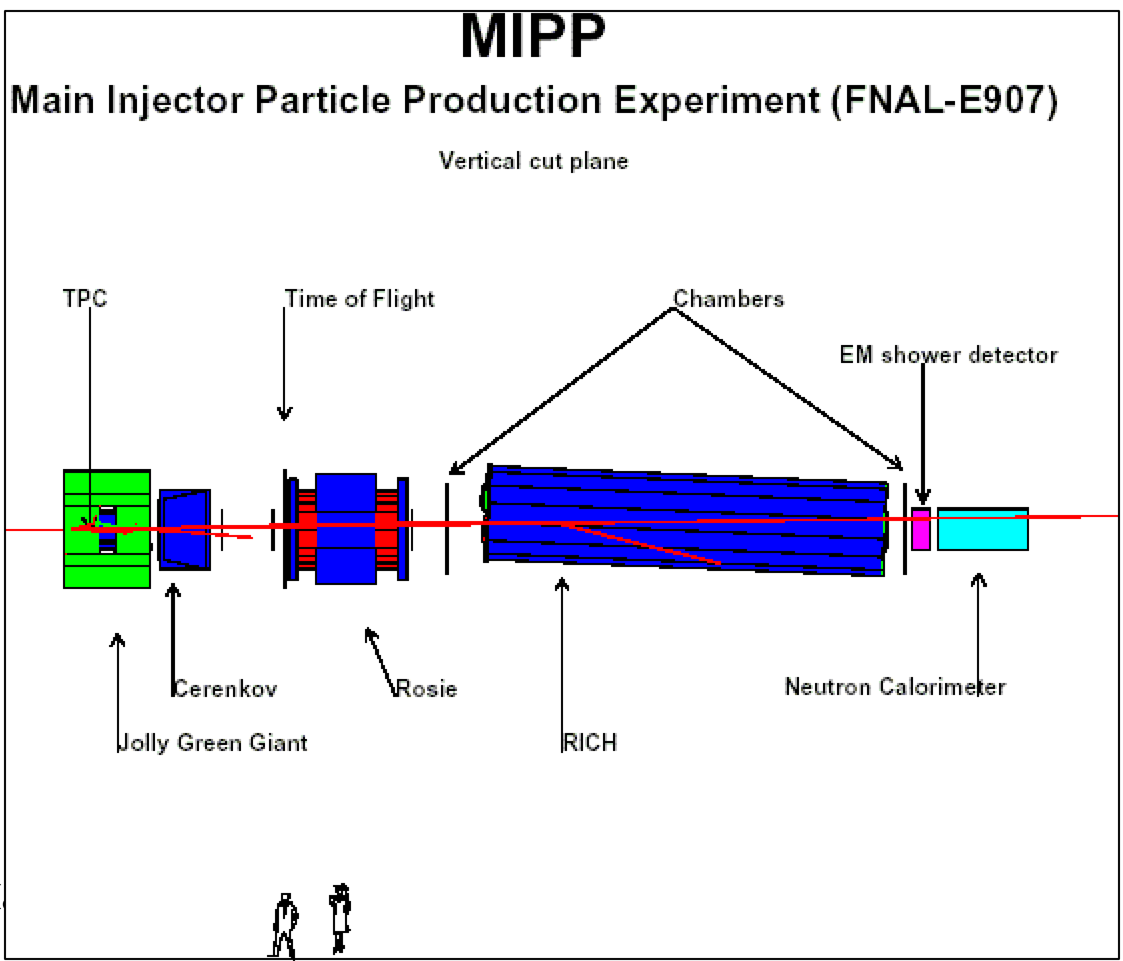


MIPP Beam characteristics

We plan to take 1,330,000 one-second slow spills on a variety of targets for 6 beam species $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ at 5,15, 25,50, 70, 90 GeV/c . We use an average of 1E10 MI protons per spill. We plan to acquire 60 million events of which 18 million are on liquid hydrogen.

Target	Physics	Data Points	Primary proton Average Intensity/spill	Total number of Primary Protons
Numi 1	MINOS	3.3	125000	2.06E+10
NUMI 2	MINOS	3.3	125000	2.06E+10
H2	Scaling	6	9.76E+09	2.93E+15
N2	Atmospheric ν	4	9.76E+09	1.95E+15
Be	pA	2	9.76E+09	9.76E+14
Be	Survey	1	9.76E+09	4.88E+14
C	Survey	1	9.76E+09	4.88E+14
Cu	pA	2	9.76E+09	9.76E+14
Cu	Survey	1	9.76E+09	4.88E+14
Pb	pA	2	9.76E+09	9.76E+14
Pb	Survey	1	9.76E+09	4.88E+14
Total		26.6		9.76E+15

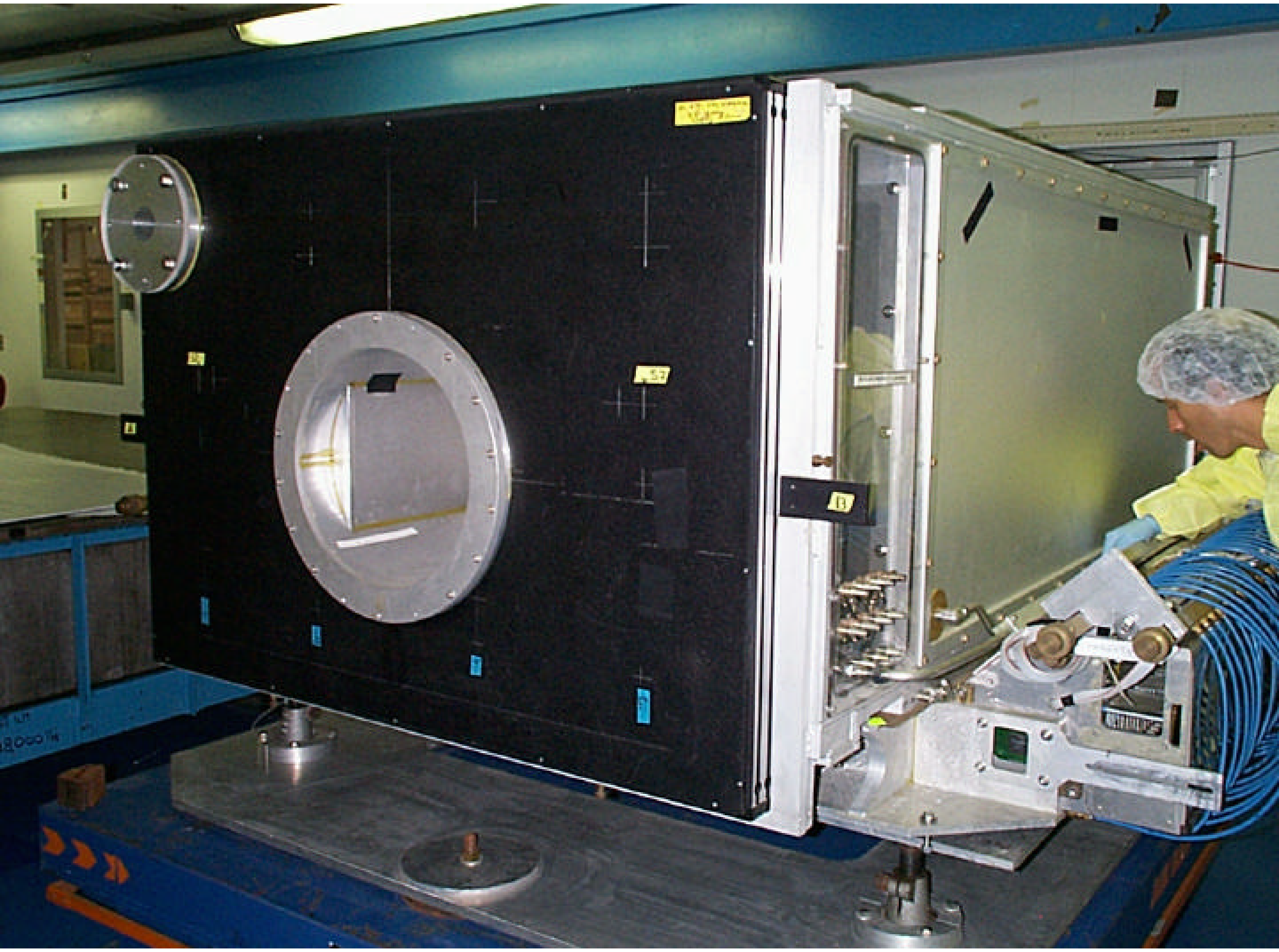

Time of Flight
TPC
Chambers
Jolly Green Giant
Cerenkov
Rosie
RICH
Neutron Calorimeter

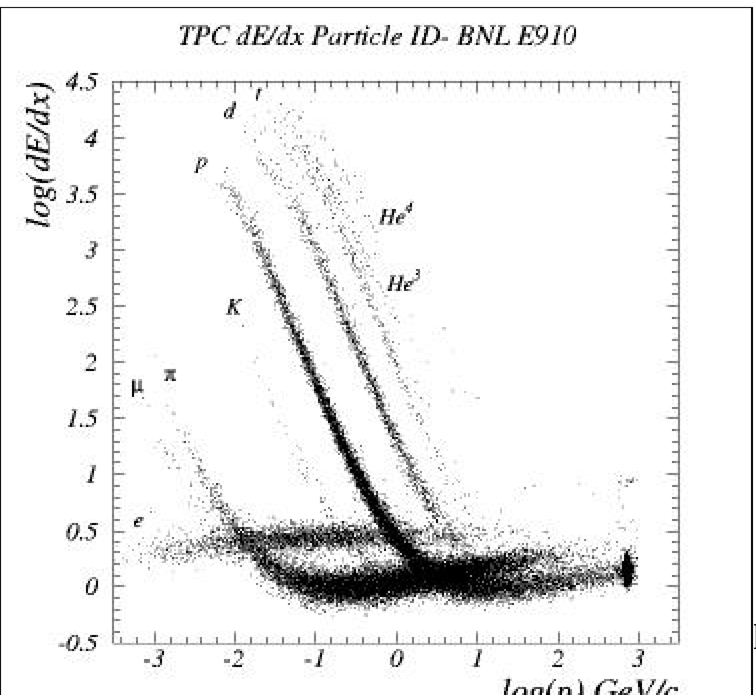

MIPP
Main Injector Particle Production Experiment (FNAL-E907)
Vertical cut plane
TPC
Time of Flight
Chambers
EM shower detector
Cerenkov
Rosie
Neutron Calorimeter
Jolly Green Giant
RICH

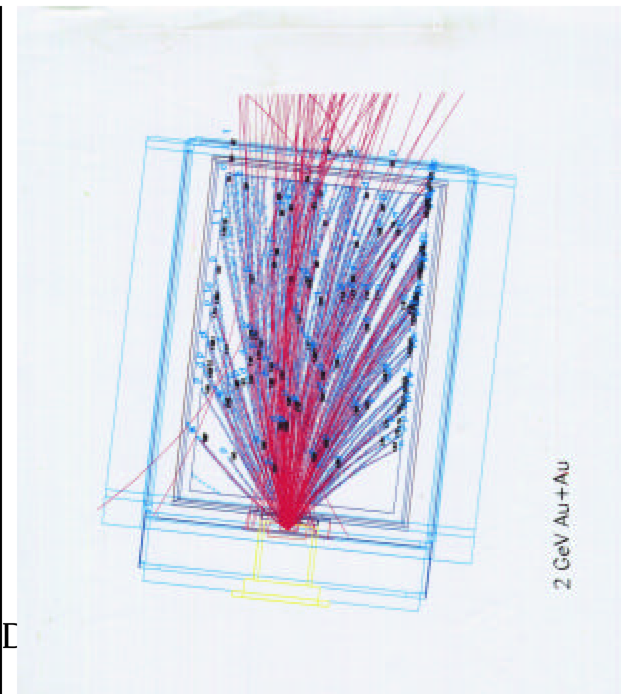
Status of MIPP Now-Collision Hall

Status of MIPP Now-Collision Hall

TPC installation







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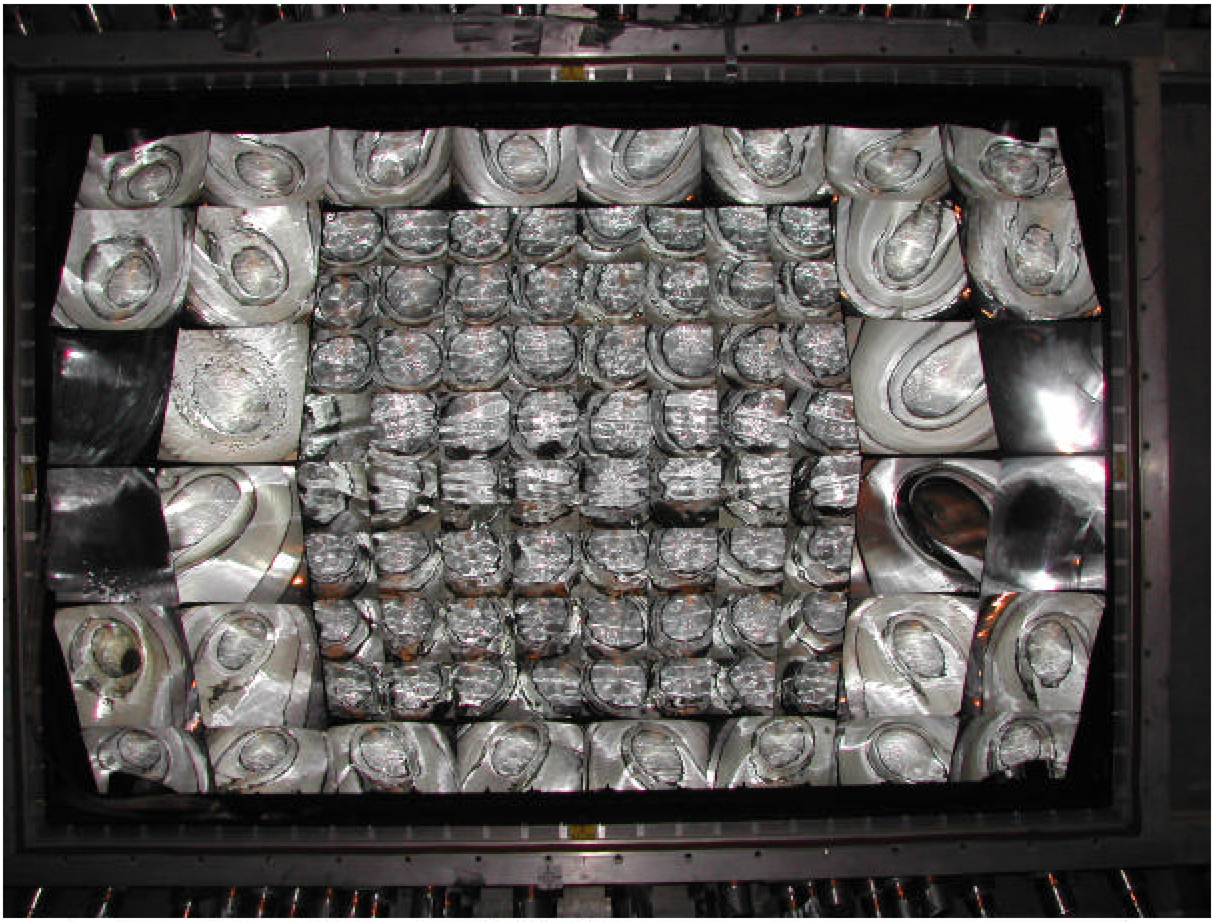
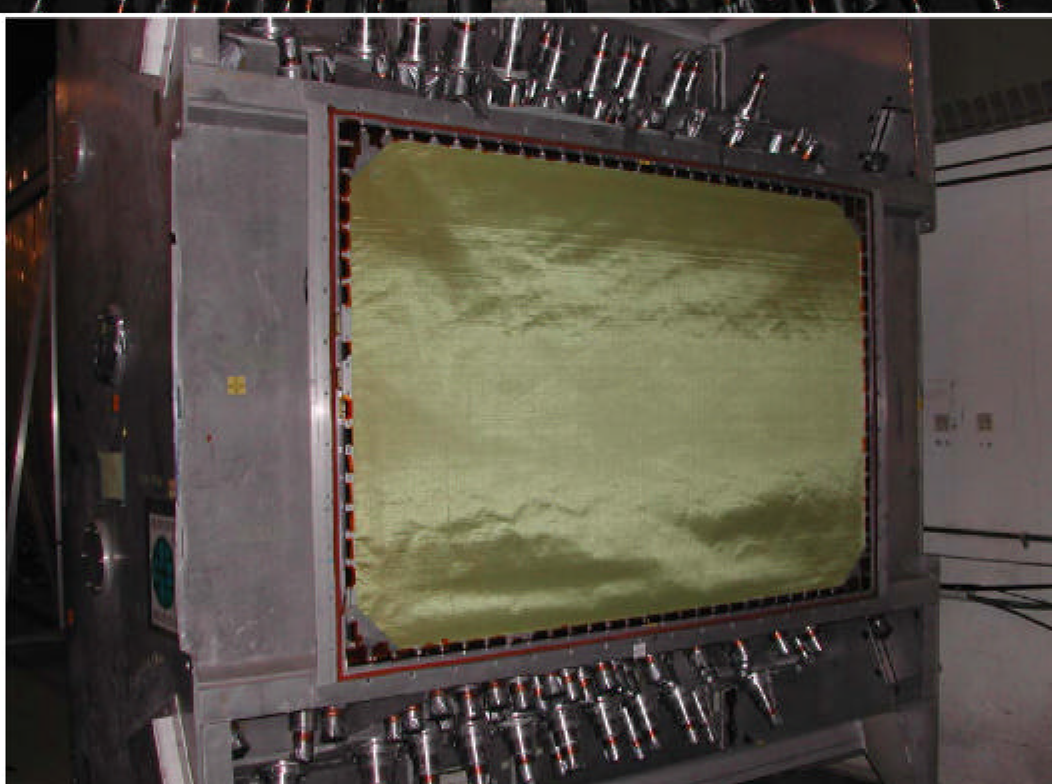
MIPP-TPC

- This Time Projection Chamber, built by the BEVALAC group at LBL for heavy ion studies currently sits in the E-910 particle production experiment at BNL, that has completed data taking. It took approximately $3million to construct.
- Can handle high multiplicity events. Time to drift across TPC=16 μs.
- Electronic equivalent of bubble chamber, high acceptance, with dE/dx capabilities. Dead time 16μs. i.e unreacted beam swept out in 8μs. Can tolerate 10^5 particles per second going through it.
- Can handle data taking rate ~60Hz with current electronics. Can increase this to ~1000 Hz with an upgrade.
- TPC dimensions of 96 x 75 x 150 cm.

MIPP Cherenkov





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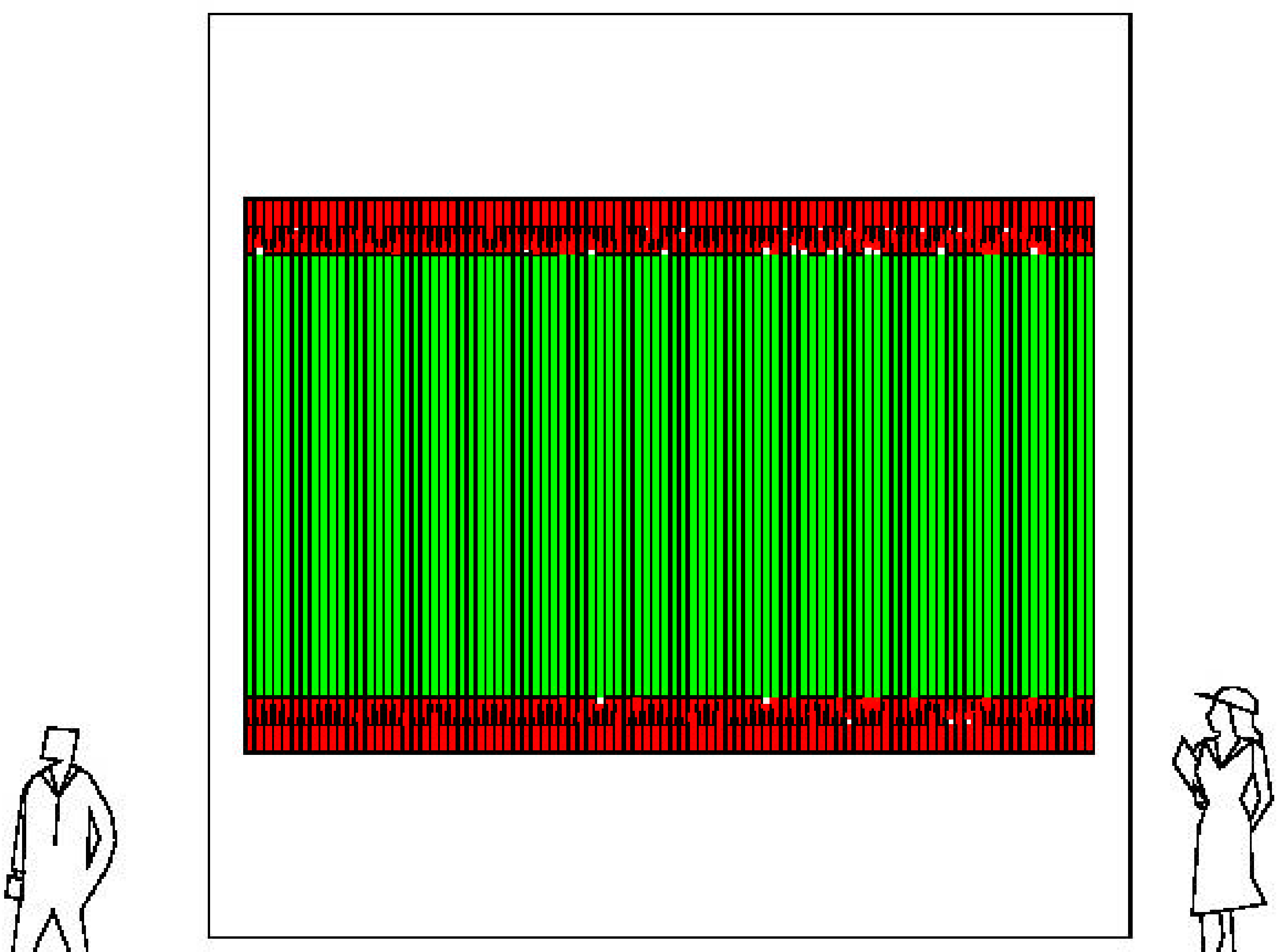
Time of Flight

- Time of flight ($220K) . Designed and built by MIPP

5cmx 5cm square scintillator bars in Rosie aperture, 10cmx10cm outside. ~ 150ps resolution.

MIPP- Time of flight system



Calorimeters

EM calorimeter followed by hadron calorimeter

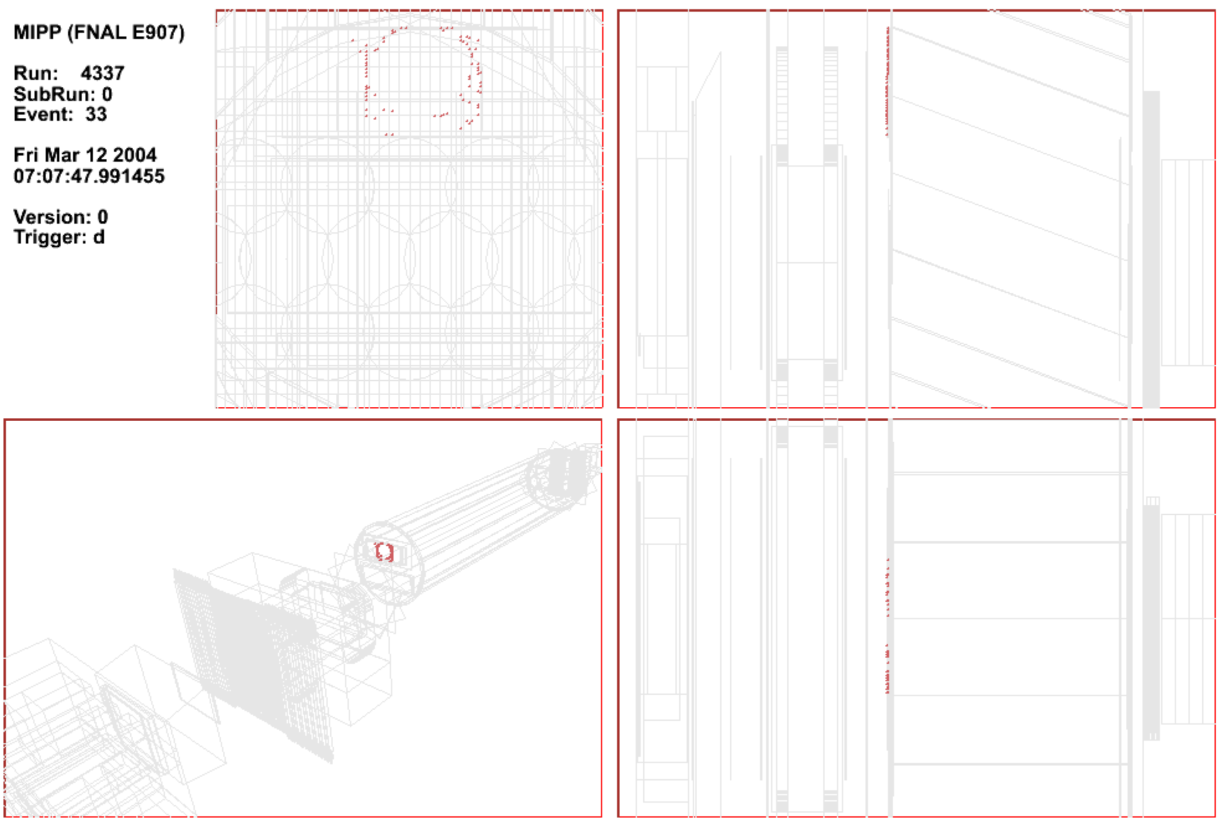
Drift and Proportional chambers

- MIPP has 3 sets of beam chambers with 4 planes each. It has 4 chambers downstream of the target also with 4 planes each. All these chambers have mini-drift.

- MIPP has in addition two large PWC's on either side of the RICH to determine the trajectories of particles through the RICH. These also have 4 planes each, but are PWC's.

RICH data

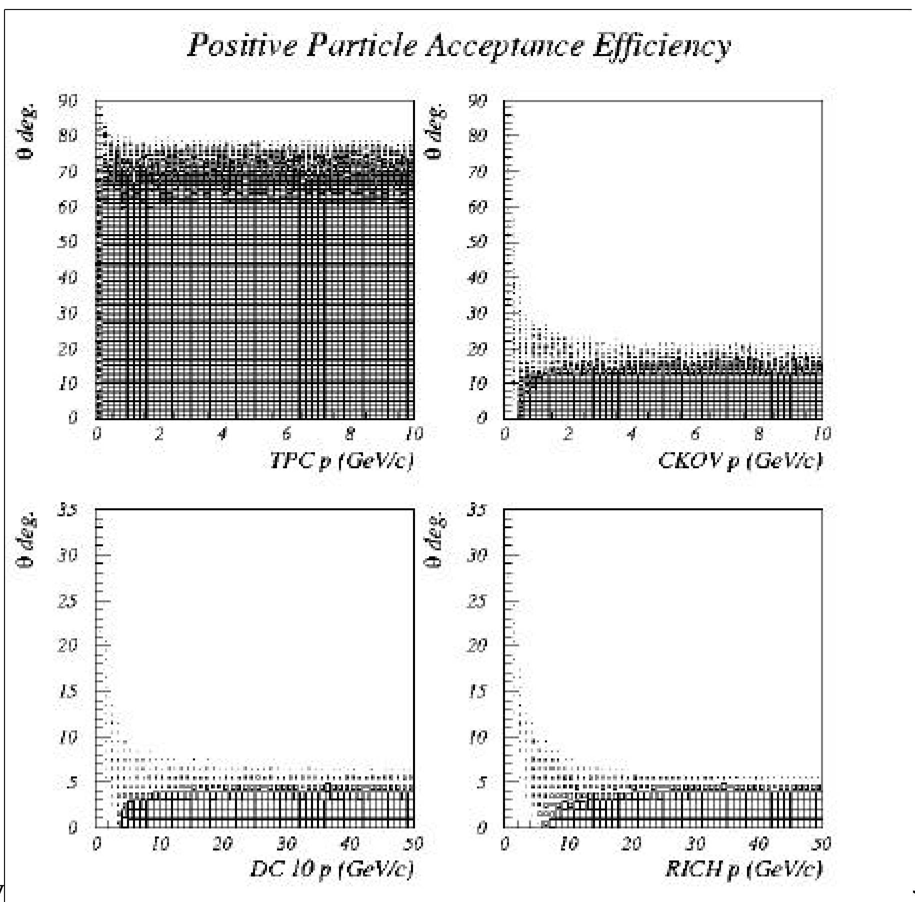
RICH being read out successfully. We see rings.



15-Mar-2004 Rajendran Raja, All Experimenters Meeting, Fermilab 9

Particle acceptances and resolutions

- a)10 Hits in TPC
- b)a hit in the Cerenkov
- c)a hit in Drift Chamber 10 (just before RICH)
- d)Passage through mid-Z plane of RICH.
- Regular Target and NUMI target
- Four cases of particles considered
- (Cumulative AND)



Particle Identification

- TPC as shown can provide 3σ separation with dE/dx up to 0.7 GeV/c for π/K and 1.1 GeV/c for K/p as well as ambiguous additional information in the relativistic rise region.
- In the intermediate region, we use a multi-cell Cerenkov detector. Light is collected by 96 phototubes from reflective mirrors. Filled with Freon 114, the Cerenkov thresholds for π, K, p are 2.5, 7.5 and 17.5 GeV/c.
- Above 7.5 GeV/c, many particles will go through to the RICH counter and be identified. We plan to use a RICH counter filled with CO_2.

Threshold	Ne	N_2	CO_2
π	12	5.7	4.9
K	42	20	17
p	80	38	33

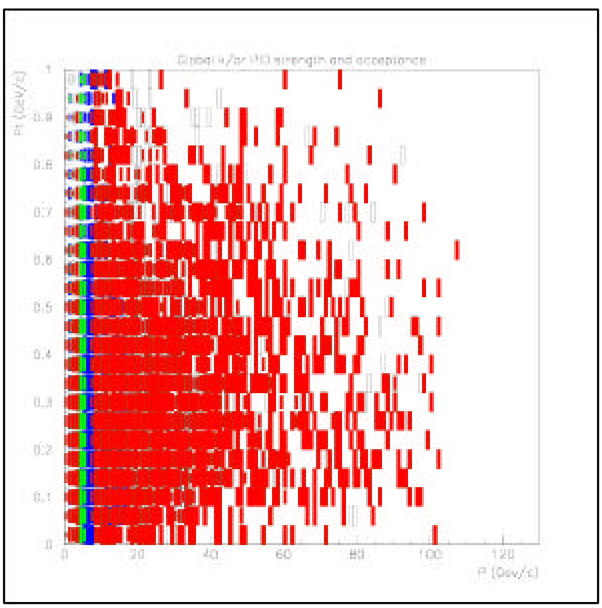
MIPP Particle ID capabilities

K/Proton separation analysis using all systems.

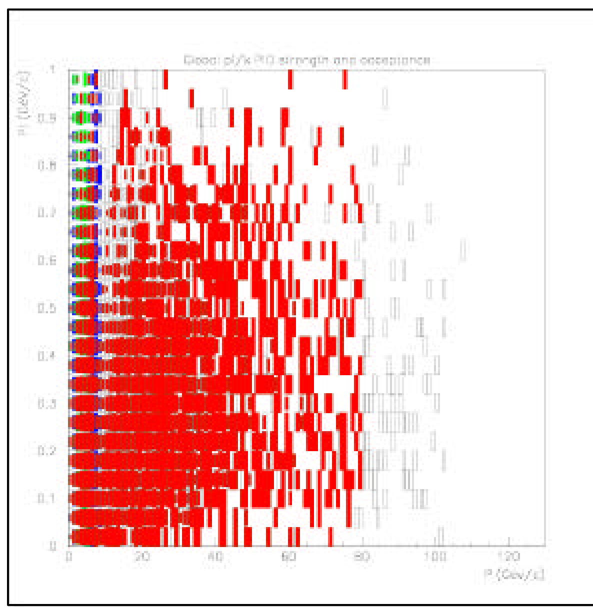
- Red = 3σ or better.
- 3σ < Green < 2σ
- 2σ < Blue < 1σ

0σ < White < 1σ

K/P separation



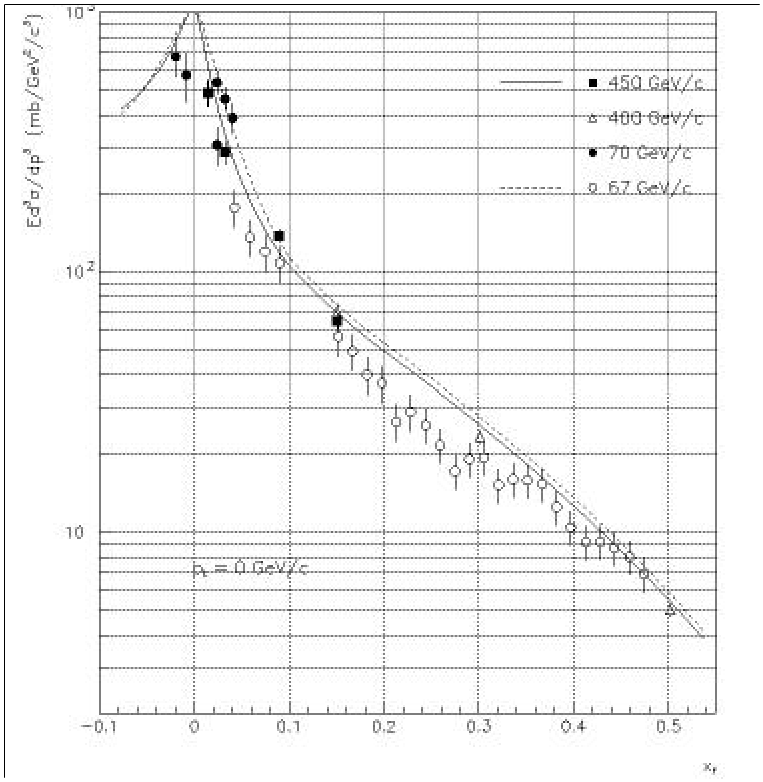
π/K separation

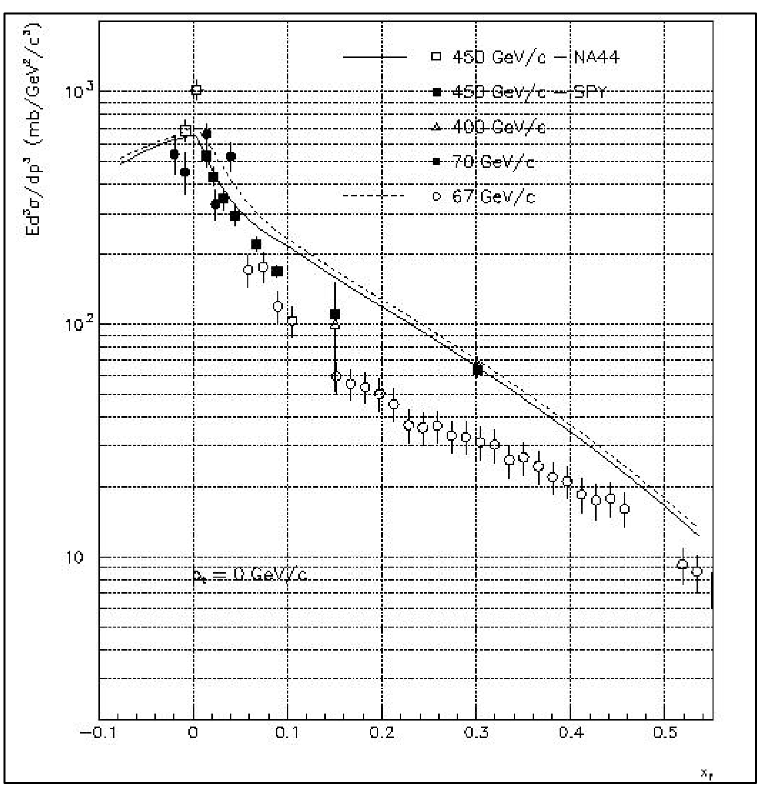


Why study non-perturbative QCD?

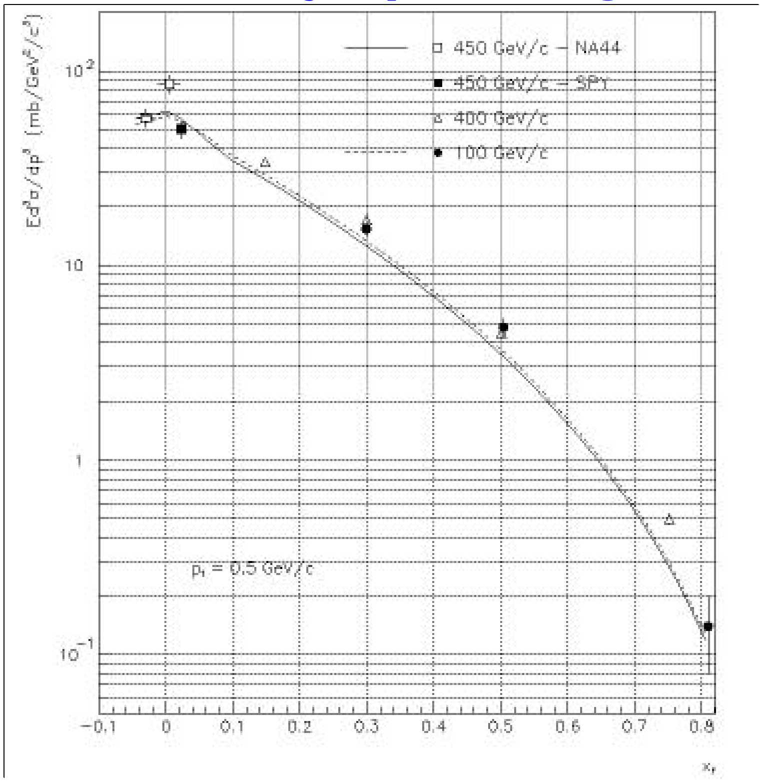
- Answer:- We do not know how to calculate a single cross section in non-perturbative QCD! This is >99% of the total QCD cross section. Perturbative QCD has made impressive progress. But it relies on structure functions for its calculations, which are non-perturbative and derived from data.
- Feynman scaling, KNO scaling, rapidity plateaus are all violated. We cannot predict elastic cross sections, diffractive cross sections, let alone inclusive or semi-inclusive processes. Regge "theory" is in fact a phenomenology whose predictions are flexible and can be easily altered by adding more trajectories.
- All existing data are old, low statistics with poor particle id.
- QCD theorist states- We have a theory of the strong interaction and it is quantum chromodynamics. Experimentalist asks– what does QCD predict? Almost as bad as the folks who claim string theory is the theory of everything! Experimentalist asks- what does it predict?

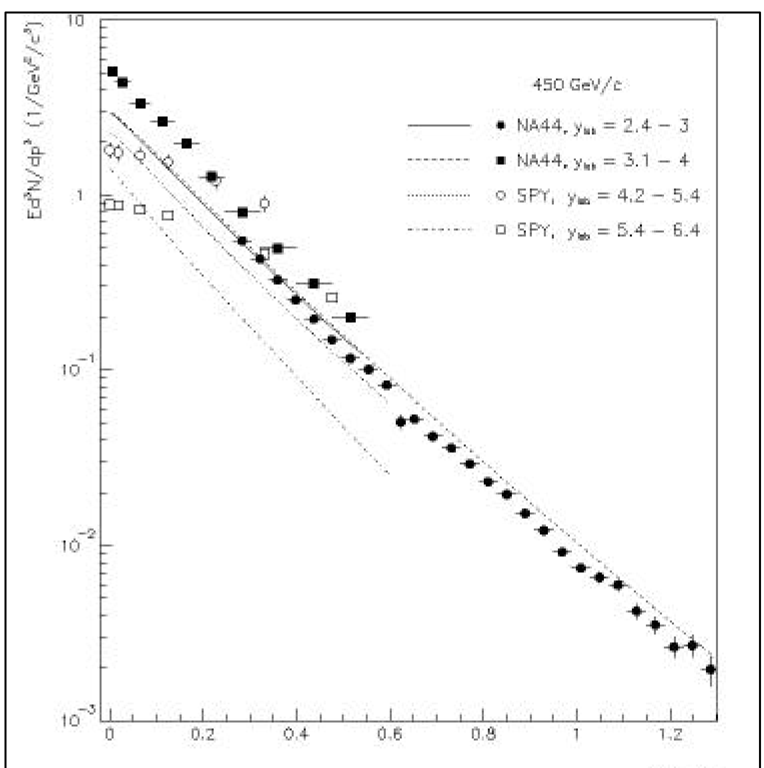
Quality of existing data





Quality of existing data





Uses of MIPP QCD data

- Mostly will come from Liquid H2 target.
- We plan to take 18 million events on LH2 with 6 beam species ($\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$)over a momentum range that spans 5 GeV/c to 90 GeV/c.
- We also plan to run Liquid deuterium, which will add np cross sections.
- We plan to re-open the study of non-perturbative QCD by publishing datasets with full particle ID in DST form in DVD's. Any person interested in testing his theory can obtain a dataset.
- We can study exclusive particle reactions with unprecedented accuracy and particle id using constrained fitting.

Uses of MIPP QCD data

- Examples of exclusive channels are

$\pi^+ p \to A_1(1270)p$	Resonance production and diffractio n
$\pi^+ p \to K^+\Sigma^+$	Strangenes s production
$K^+ p \to pp\overline{\Lambda}$	strangenes s and Baryon number production
$K^+ p \to \Delta^+ K^0 \pi^+$	charge exchange and resonance production
$p^+ p \to ppK^+K^-$	Difraction , strangenes s production
$p^+ p \to pp\pi^+\pi^-$	Diffractiv e Dissociati on, Pomerons
$\pi^- p \to \pi^0 n$	Classic ρ exchange reaction
$\pi^- p \to K_*^0(892)\Lambda$	Strangenes s resonance production
$K^- p \to K_3^{*-}(1780)p$	Exotic resonance production
$K^- p \to pK^-$	Strange Baryon exchange
$p^- p \to 3\pi^+ 3\pi^-$	Annihilati on
$p^- p \to p\overline{n}\pi^-$	$\overline{\text{p}}$ diffractio n (4C if we detect $\overline{\text{n}}$, else 1C)

A more complete list of exclusive channels in all the beam species is available at

http://ppd.fnal.gov/experiments/e907/notes/MIPPnotes/public/pdf/MIPP0010/MIPP0010.pdf

Uses of MIPP QCD data

- Missing neutral channels are available as 1C fit.
- Diffraction in 6 beam species with particle id.
- Annihilation as a function of beam momentum
- Flavor propagation in nuclei $K^{\pm}$ propagating through nuclei. How fast is strangeness exchanged?
- Exotic resonances such as glueballs and pentaquarks can be searched for. Unprecedented particle ID and acceptance capabilities as well as the presence of 6 beam species in one experiment will help unravel the nature of the found objects.
- Upgrading the TPC electronics will enable MIPP to take data at 1000HZ instead of the current 60HZ. This will enhance the physics potential of MIPP.

General scaling law of particle fragmentation

- States that the ratio of a semi-inclusive cross section to an inclusive cross section

$$\frac{f(a+b\rightarrow c+X_{subset})}{f(a+b\rightarrow c+X)}\equiv\frac{f_{subset}(M^2,s,t)}{f(M^2,s,t)}=b_{subset}(M^2)$$

- where M^2,s and t are the Mandelstam variables for the missing mass squared, CMS energy squared and the momentum transfer squared between the particles a and c. PRD18(1978)204.
- Using EHS data, we have tested and verified the law in 12 reactions (DPF92) but only at fixed s.
- The proposed experiment will test the law as a function of s and t for various particle types a ,b and c for beam energies between ~5 GeV/c and 120 GeV/c to unprecedented statistical and systematic accuracy in 36 reactions.

Estimation of the Annihilation component in pbar-p interactions

- **R.Raja, Phys.Rev.D16:142,1977**
- Conventional method is to subtract pp cross section from pbar-p cross sections. Works well for total cross section, and multiplicity cross sections. Works for neutral pion inclusive cross sections but FAILS for charged pion inclusive cross sections.

Estimation of the annihilation component

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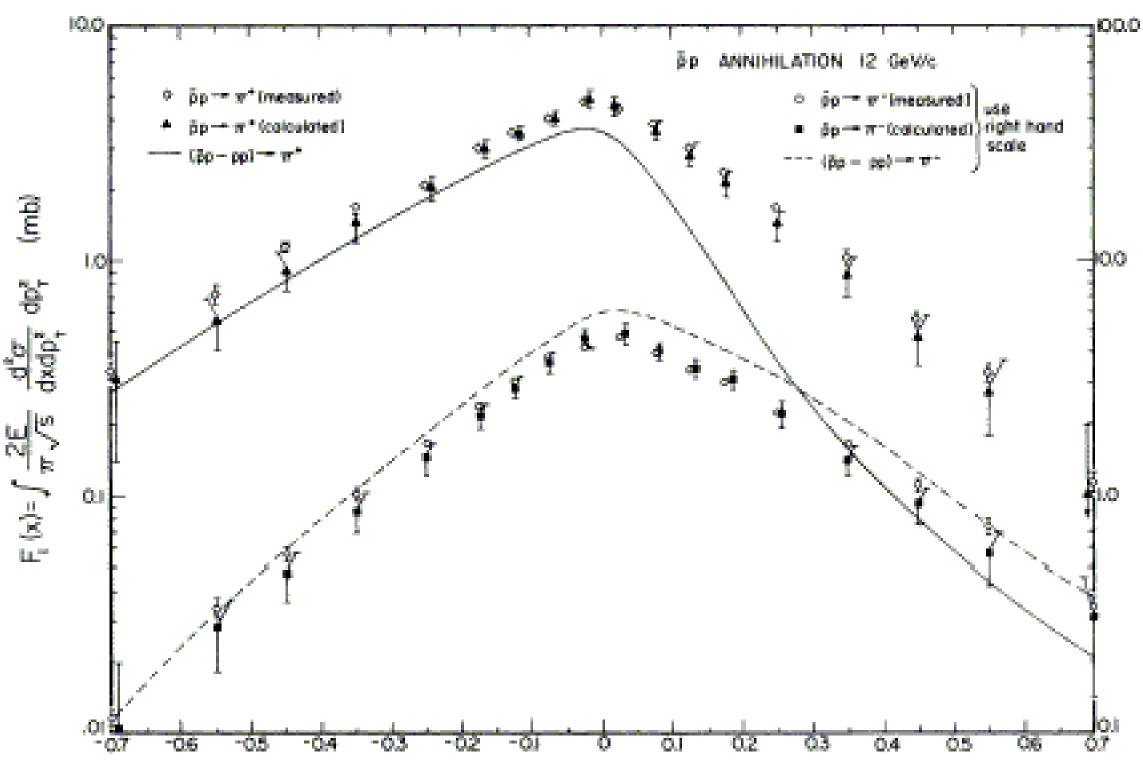


FIG. 1. Comparison of explicit annihilation data at 12 GeV/c with predictions of the derived formulas. Note the different scales for the two sets of data. The curves are the predictions of the charge-symmetry-violating subtraction formulas.

Estimation of the annihilation component

$$\bar{p}p \to p^{+} + X \equiv \bar{p}^{+} \;\; ; \;\; \bar{p}p \to p^{-} + X \equiv \bar{p}^{-}$$

$$\bar{p}p \to p^{+} + X\,(ann.) \equiv \bar{p}_A^{\;+} \; ; \;\; \bar{p}p \to p^{-} + X\,(ann.) \equiv \bar{p}_A^{\;-}$$

$$pp \to p^{+} + X \equiv p^{+} \;\; ; pp \to p^{-} + X \equiv p^{-}$$

Denote by Π the Parity inversion operator

Then

$$\Pi\bar{p}^{+} = \bar{p}^{-}; \Pi\bar{p}^{-} = \bar{p}^{+}; \Pi p^{+} = p^{+}; \Pi p^{-} = p^{-}$$

$$\Pi\bar{p}_A^{\;+} = \bar{p}_A^{\;-}; \Pi\bar{p}_A^{\;-} = \bar{p}_A^{\;+}$$

whereas for $p^{0's}$, both $\bar{\text{p}}$p and pp are even under inversion.

- So π^0 production in annihilation information is available by subtraction

$$\bar{p}_A^{0} = \bar{p}^{0} - p^{0}$$

- but not $\pi^{\pm}$.

$$\bar{p}_A^{+} \neq \bar{p}^{+} - p^{+} \qquad\qquad \bar{p}_A^{-} \neq \bar{p}^{-} - p^{-}$$

Estimation of the annihilation component

- However, the sum of π^+ and π^- is even under inversion, so we can write

$$\overline{p}_A^+ + \overline{p}_A^- = (\overline{p}^+ + \overline{p}^-) - (p^+ + p^-)$$

- However, the term $\overline{p}_A^+ - \overline{p}_A^-$ is odd under parity inversion and cannot be obtained from pp data. An expression that can be written for the odd term that treats annihilation and non-annihilation symmetrically is

$$\frac{\overline{p}_A^+ - \overline{p}_A^-}{\overline{p}_A^+ + \overline{p}_A^-} = \frac{\overline{p}_N^+ - \overline{p}_N^-}{\overline{p}_N^+ + \overline{p}_N^-} = \frac{\overline{p}^+ - \overline{p}^-}{\overline{p}^+ + \overline{p}^-}$$

Estimation of the annihilation component

- This leads to

$$\overline{p}_A^{+} = \left(\frac{(\overline{p}^{+} + \overline{p}^{-}) - (p^{+} + p^{-})}{(\overline{p}^{+} + \overline{p}^{-})} \right) \overline{p}^{+}$$

- And
-

$$\overline{p}_A^{-} = \left(\frac{(\overline{p}^{+} + \overline{p}^{-}) - (p^{+} + p^{-})}{(\overline{p}^{+} + \overline{p}^{-})} \right) \overline{p}^{-}$$

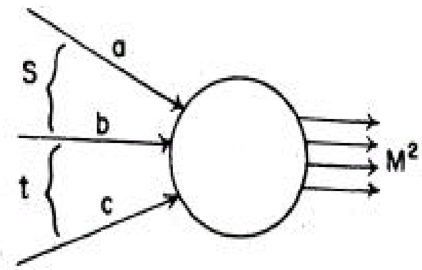
Explanation for the charge asymmetry relation

- See "Observation of New regularity in hadronic spectra", R.Raja Phys.Rev.D 18 (1978)204.
- The relation

$$\frac{\overline{p}_A^+ - \overline{p}_A^-}{\overline{p}_A^+ + \overline{p}_A^-} = \frac{\overline{p}_N^+ - \overline{p}_N^-}{\overline{p}_N^+ + \overline{p}_N^-} = \frac{\overline{p}^+ - \overline{p}^-}{\overline{p}^+ + \overline{p}^-}$$

can be explained if one posits that the three body scattering happens in two steps. Formation of the fireball followed by its decay. Similar to the Bohr Compound nucleus hypothesis

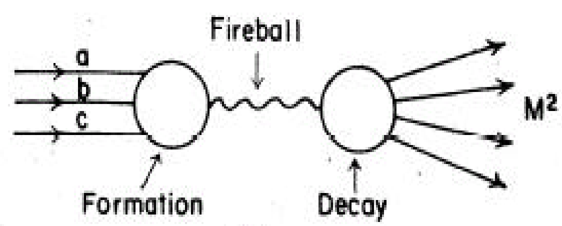
Scaling Law



(a)

$$s\,(abc \rightarrow X) = F(M^2, s, t)D_X(M^2)$$

$$s\,(abc \rightarrow X_s) = F(M^2, s, t)D_{X_s}(M^2)$$



(b)

$$\frac{s\,(abc \rightarrow X_{sub})}{s\,(abc \rightarrow X)} = \frac{F(M^2, s, t)D_{X_{sub}}(M^2)}{F(M^2, s, t)D_X(M^2)} = a_{sub}(M^2)$$

- Continuing on to physical t values, one gets

$$\frac{f\,(ab \rightarrow \bar{c} + X_{sub})}{f\,(ab \rightarrow \bar{c} + X)} = a_{sub}(M^2)$$

Scaling law

- Applying to annihilations, one gets

$$\frac{\overline{p}_A^{+}(M^2,s,t)}{\overline{p}^{+}(M^2,s,t)} = a_A^{+}(M^2)$$

$$\frac{\overline{p}_A^{-}(M^2,s,t)}{\overline{p}^{-}(M^2,s,t)} = a_A^{-}(M^2)$$

$a_A^{+}(M^2) = a_A^{-}(M^2)$ due to C symmetry

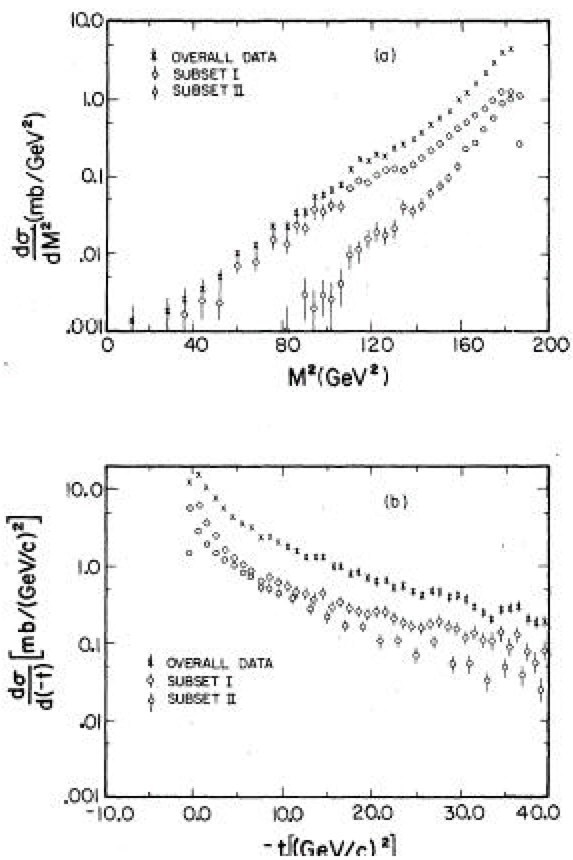
leading to

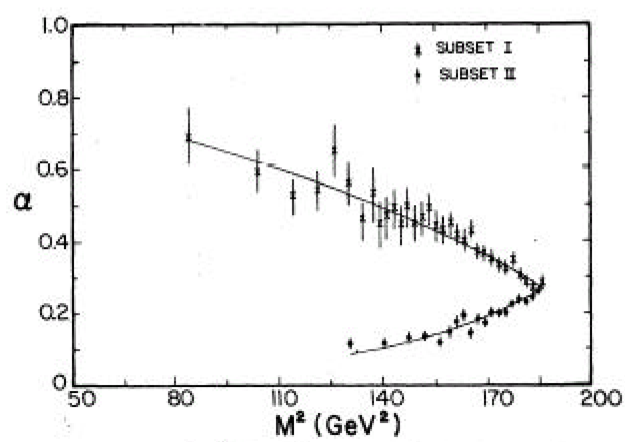
$$\frac{\overline{p}_A^{+} - \overline{p}_A^{-}}{\overline{p}_A^{+} + \overline{p}_A^{-}} = \frac{\overline{p}_N^{+} - \overline{p}_N^{-}}{\overline{p}_N^{+} + \overline{p}_N^{-}} = \frac{\overline{p}^{+} - \overline{p}^{-}}{\overline{p}^{+} + \overline{p}^{-}}$$

- This factorization and decay is general. So does it apply to other subsets? The answer is yes!

Scaling Law

- 100 GeV/c $\bar{p}p$ data is divided into 2 subsets of multiplicity.
- Subset I= multiplicities 2,4,6
- Subset II= multiplicities 12,14,16





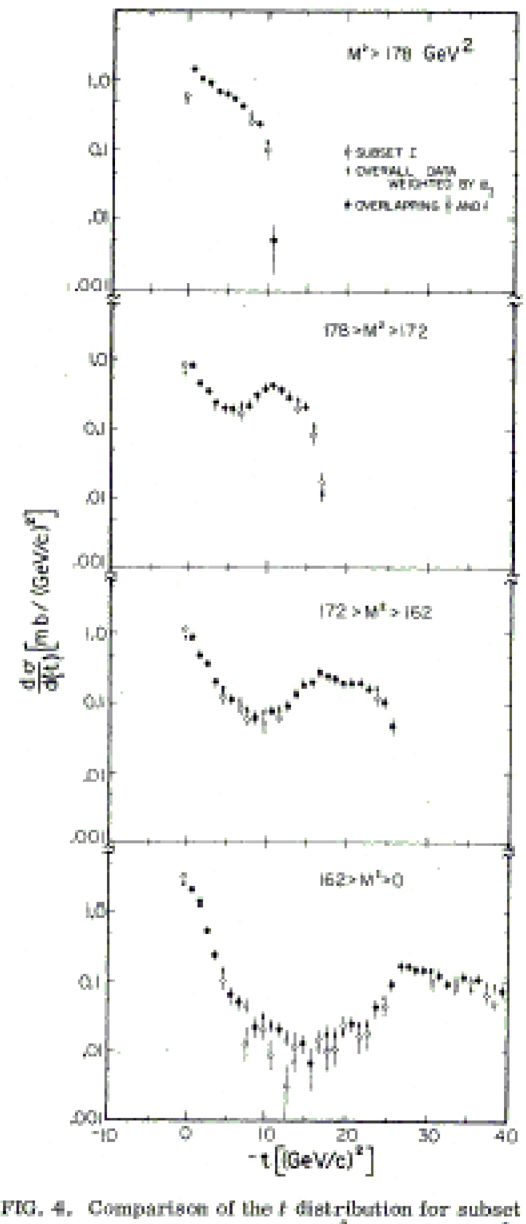


FIG. 4. Comparison of the t distribution for subset I with overall data weighted by $\alpha_I(M^2)$ for various M^2 ranges.

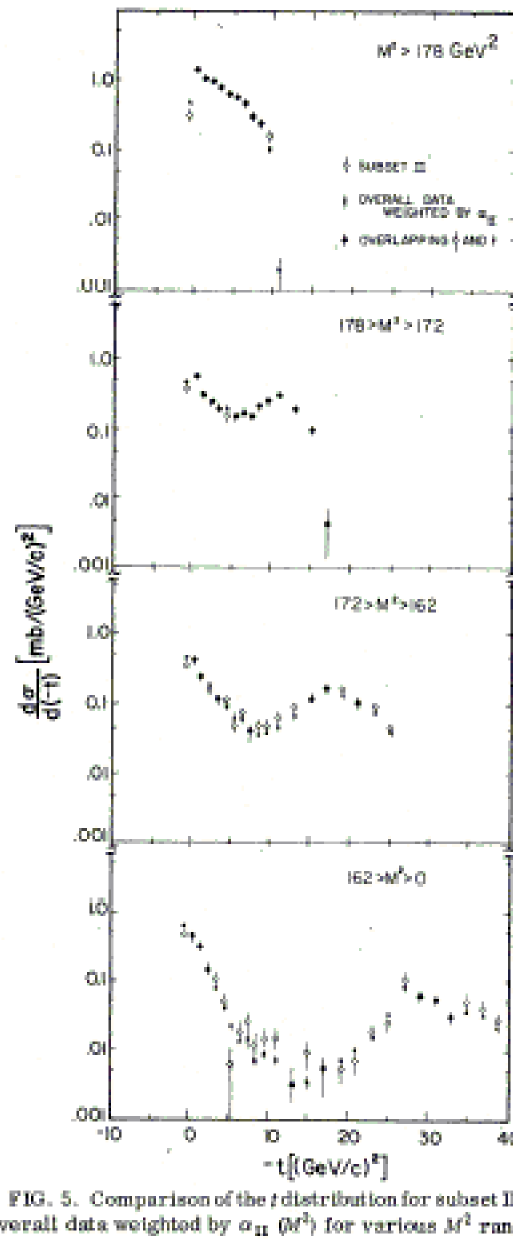


FIG. 5. Comparison of the t distribution for subset II with overall data weighted by $\alpha_{II}(M^2)$ for various M^2 ranges.

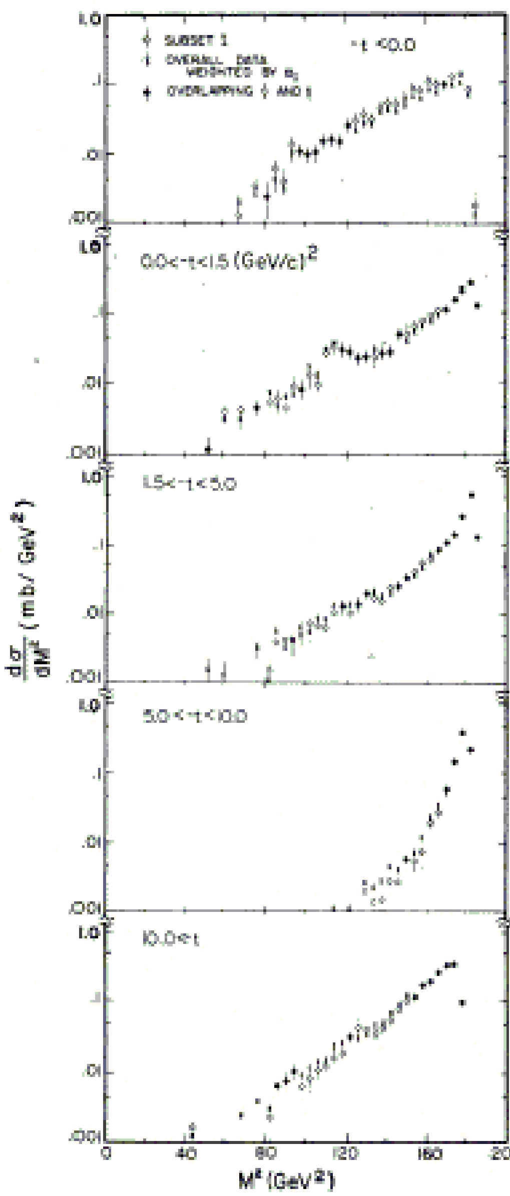


FIG. 6. Comparison of the M^2 distribution for subset I with overall data weighted by α_I (M^2) for various t ranges.

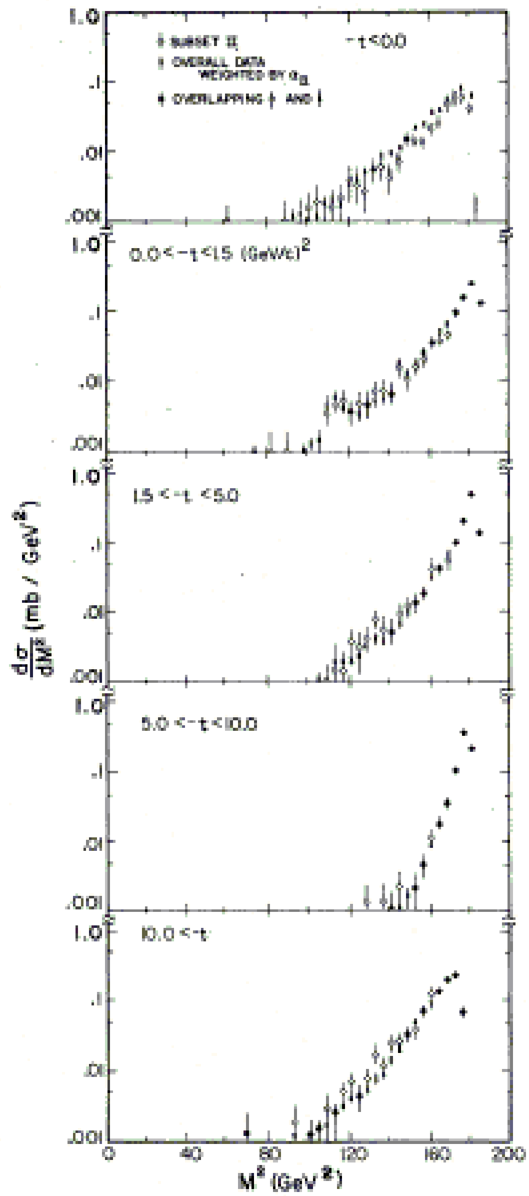


FIG. 7. Comparison of the M^2 distribution for subset II with overall data weighted by α_{II} (M^2) for various t ranges.

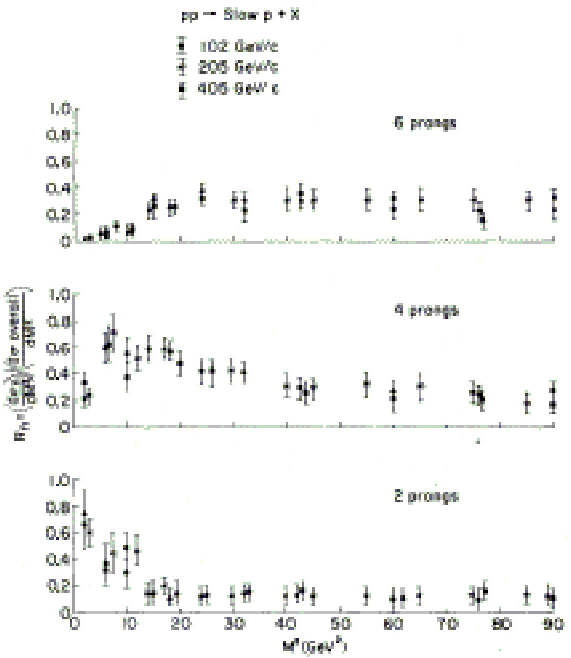


FIG. 8. The ratio of the semi-inclusive cross section to the overall cross section vs M^2 for 2, 4, and 6 prongs at beam momenta 102, 205, and 405 GeV/c.

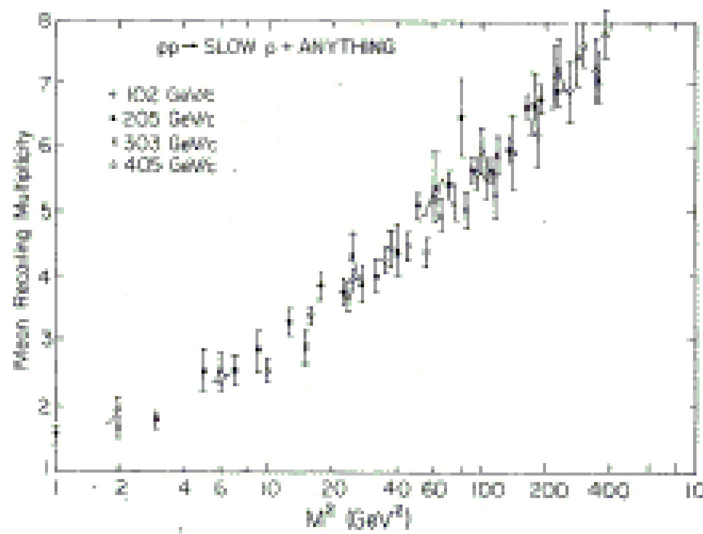


FIG. 9. The mean recoiling multiplicity as a function of M^2 at beam momenta 102, 205, 303, and 405 GeV/c.

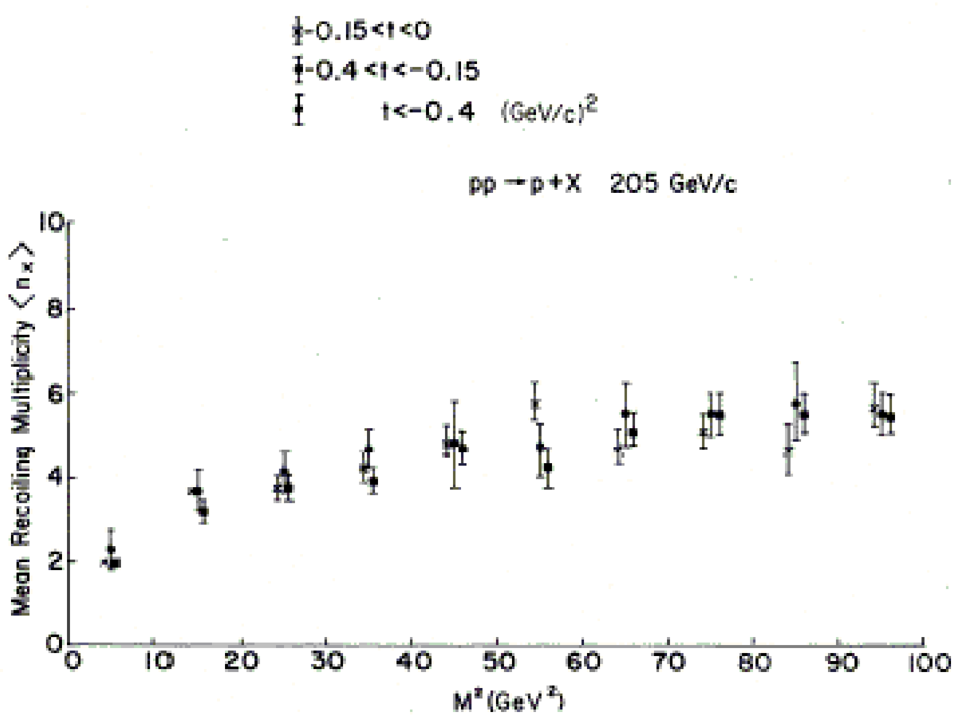
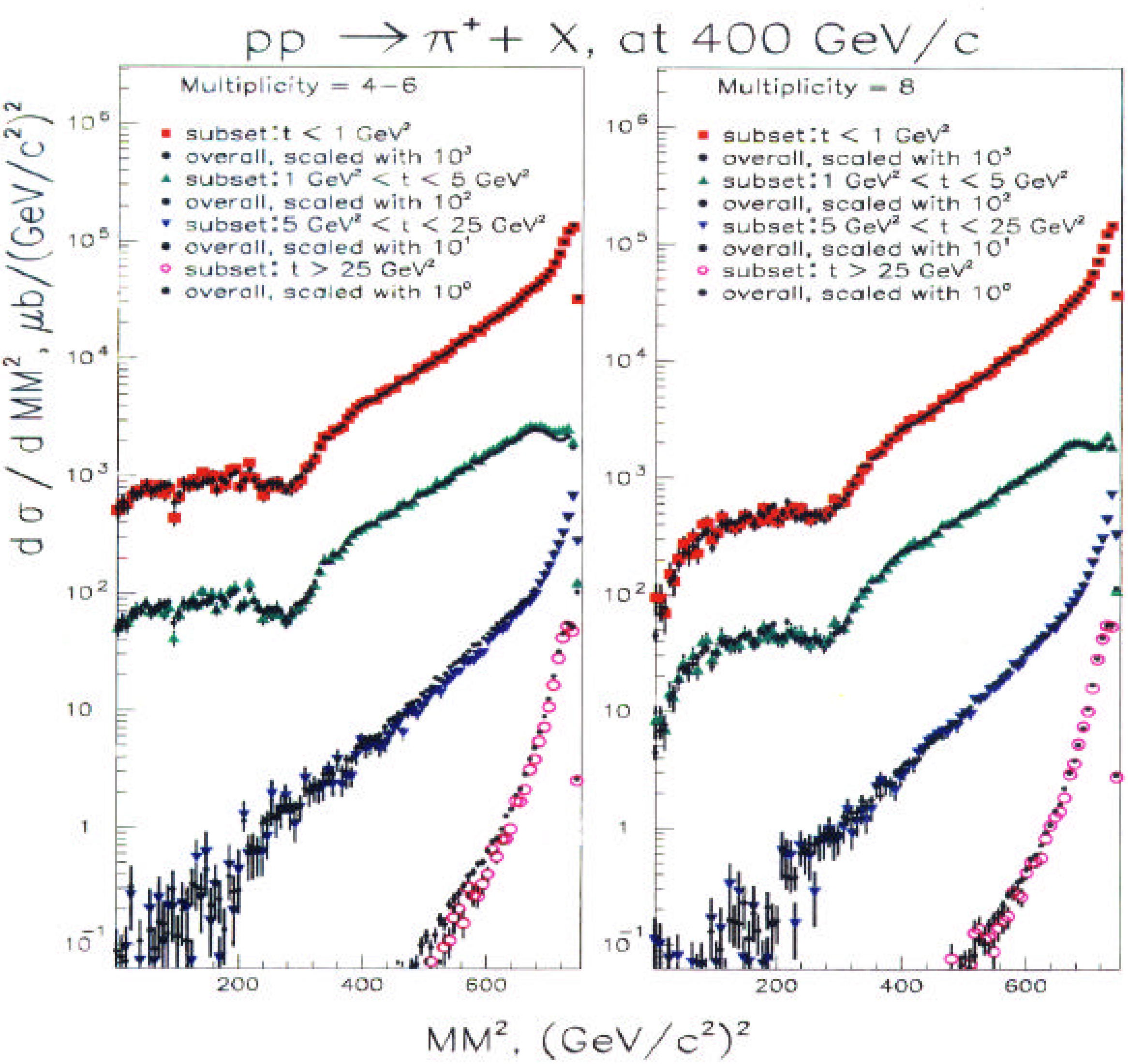


FIG. 10. The mean recoiling multiplicity as a function of M^2 for various t ranges at 205 GeV/c.

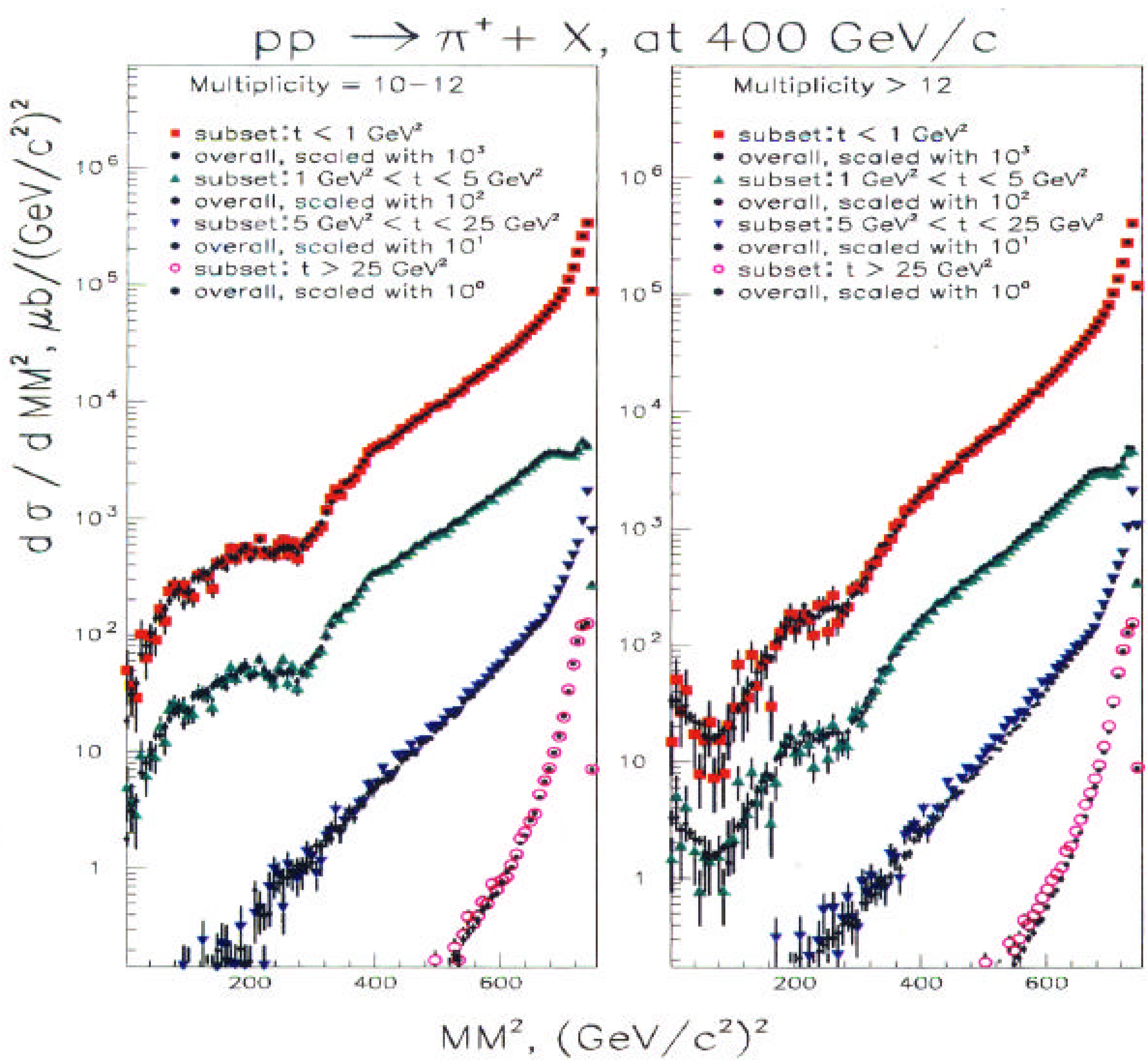
European Hybrid Spectrometer data

- 1 million events in EHS would have taken 3 years to analyze- Scan measure and track match. Incomplete particle id. Only data available at fixed s. Can test t independence. It takes MIPP ~ 8 hours to acquire 1 Million events, fully track matched and particle id'd.
- We have verified the scaling law in 12 reactions using EHS data at fixed s. (Y.Fisyak,R.Raja, Proceedings of the DPF1992 conference)

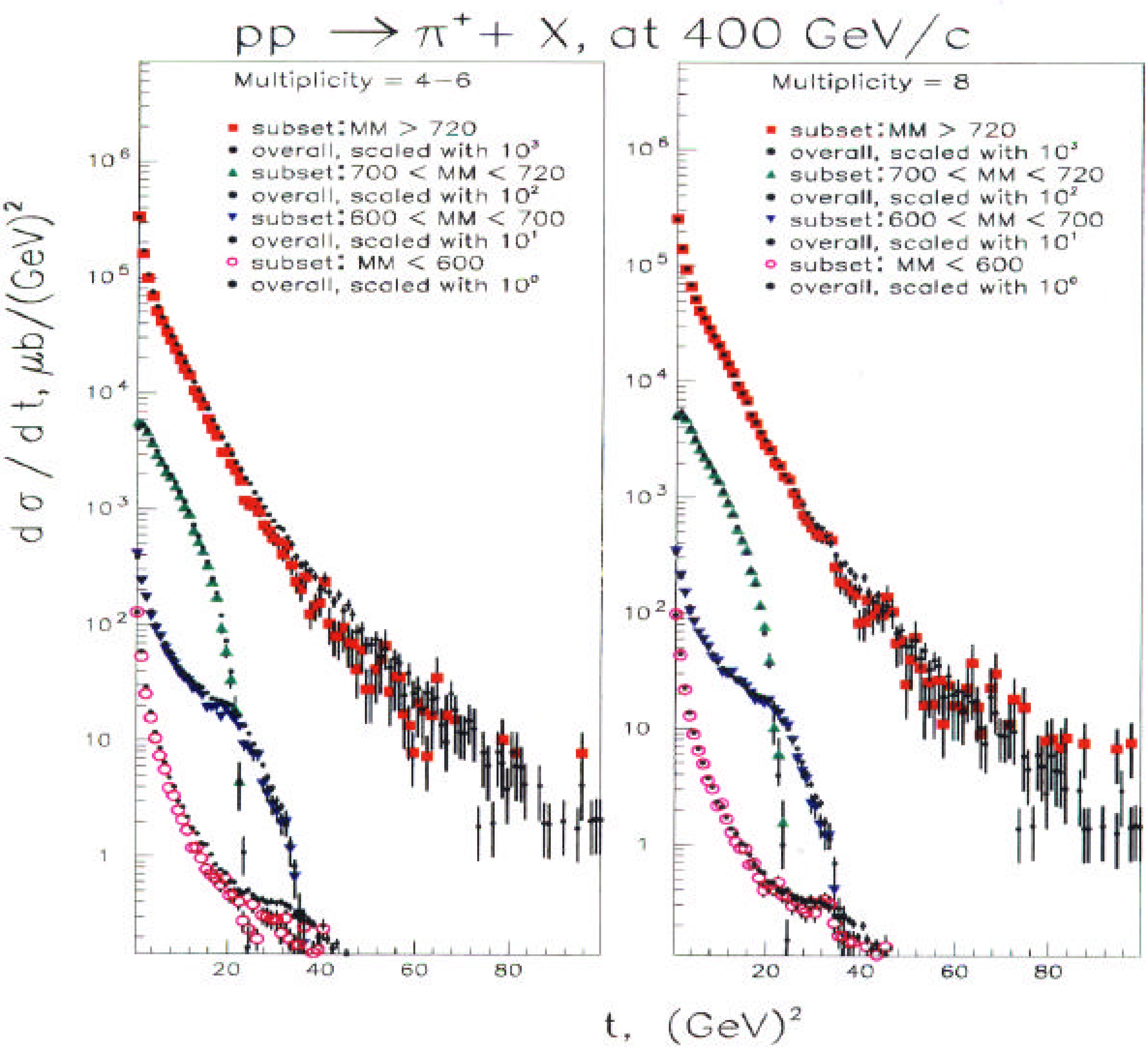
Scaling Law-EHS results



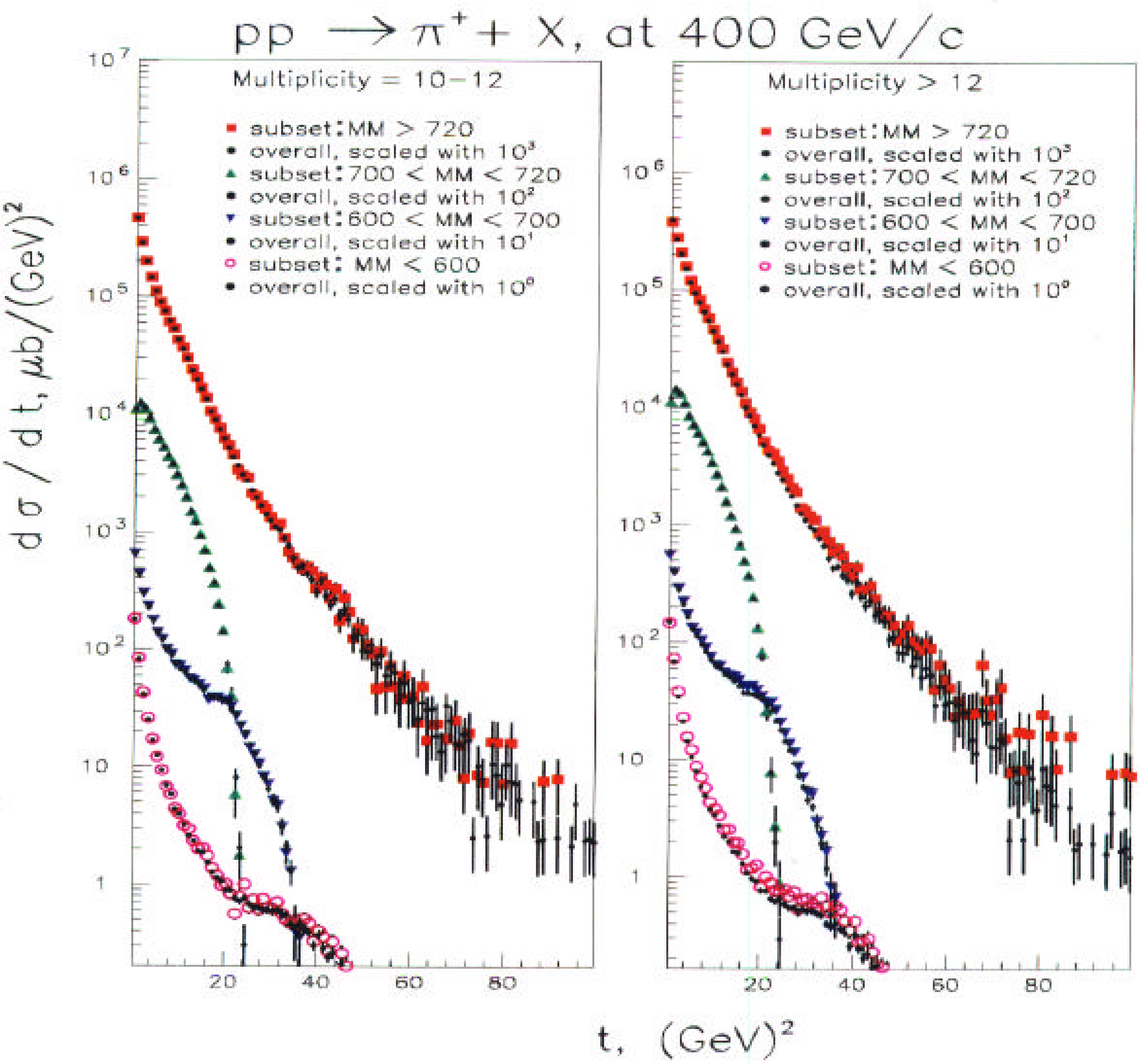
Scaling Law-EHS results



Scaling law -EHS results



Scaling Law -EHS results



Scaling Law tests with MIPP

- MIPP will test the scaling law with 36 reactions both in s and in t.
- Positive beam reactions

1	p^{+}	+	**p**	------->	p^{+}	+	X
2	p^{+}	+	**p**	------->	K^{+}	+	X
3	p^{+}	+	**p**	------->	**p**	+	X
4	p^{+}	+	**p**	------->	p^{-}	+	X
5	p^{+}	+	**p**	------->	K^{-}	+	X
6	p^{+}	+	**p**	------->	$\mathbf{p}^{-}$	+	X
7	K^{+}	+	**p**	------->	p^{+}	+	X
8	K^{+}	+	**p**	------->	K^{+}	+	X
9	K^{+}	+	**p**	------->	**p**	+	X
10	K^{+}	+	**p**	------->	p^{-}	+	X
11	K^{+}	+	**p**	------->	K^{-}	+	X
12	K^{+}	+	**p**	------->	$\mathbf{p}^{-}$	+	X
13	**p**	+	**p**	------->	p^{+}	+	X
14	**p**	+	**p**	------->	K^{+}	+	X
15	**p**	+	**p**	------->	**p**	+	X
16	**p**	+	**p**	------->	p^{-}	+	X
17	**p**	+	**p**	------->	K^{-}	+	X
18	**p**	+	**p**	------->	$\mathbf{p}^{-}$	+	X

Scaling law tests with MIPP

Negative beam reactions

19	p^-	+	**p**	------->	p^+	+	X
20	p^-	+	**p**	------->	K^+	+	X
21	p^-	+	**p**	------->	**p**	+	X
22	p^-	+	**p**	------->	p^-	+	X
23	p^-	+	**p**	------->	K^-	+	X
24	p^-	+	**p**	------->	$\mathbf{p}^-$	+	X
25	K^-	+	**p**	------->	p^+	+	X
26	K^-	+	**p**	------->	K^+	+	X
27	K^-	+	**p**	------->	**p**	+	X
28	K^-	+	**p**	------->	p^-	+	X
29	K^-	+	**p**	------->	K^-	+	X
30	K^-	+	**p**	------->	$\mathbf{p}^-$	+	X
31	$\mathbf{p}^-$	+	**p**	------->	p^+	+	X
32	$\mathbf{p}^-$	+	**p**	------->	K^+	+	X
33	$\mathbf{p}^-$	+	**p**	------->	**p**	+	X
34	$\mathbf{p}^-$	+	**p**	------->	p^-	+	X
35	$\mathbf{p}^-$	+	**p**	------->	K^-	+	X
36	$\mathbf{p}^-$	+	**p**	------->	$\mathbf{p}^-$	+	X

Among the 36, there are 15 crossing symmetry relations and 3 C symmetry relations

Scaling law tests with MIPP

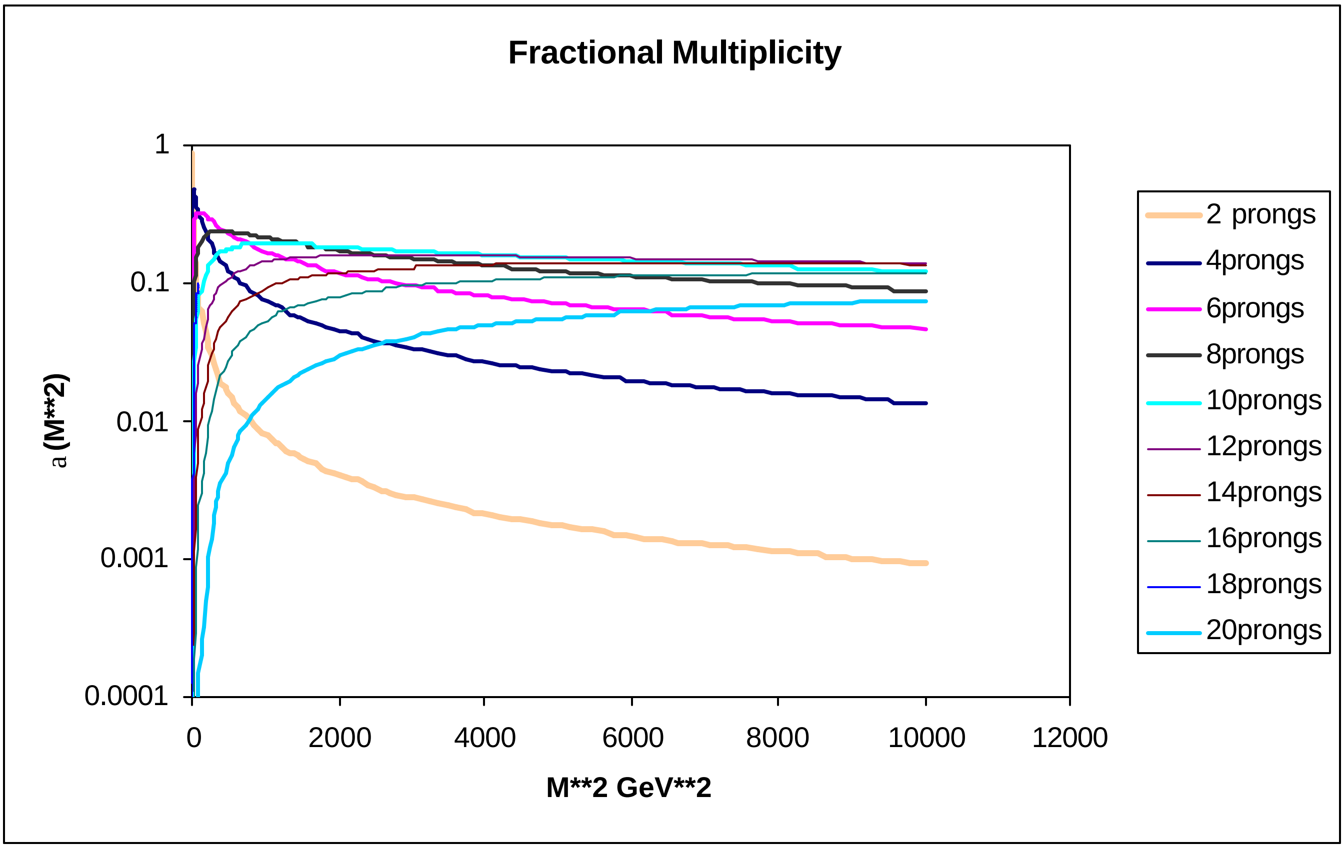
- For instance the functions $\alpha_s(M^2)$ by crossing symmetry must be the same for $\pi^+ p \rightarrow \pi^+ + X$ and $\pi^- p \rightarrow \pi^- + X$.
- Similarly

$$\overline{p}p \rightarrow p^{+} + X \text{ and } p^{-} p \rightarrow p + X$$

Have the same $\alpha_s(M^2)$. So a diffractive process is linked to a central production process!

Scaling law tests with MIPP

These are the branching fractions of the fireball as a function of M^2. Central production reactions peak at x=0.



Since $x \approx 1 - \frac{M^2}{s}$, central production cross sections will move in the above plot with s. Diffraction cross sections will peak at small M^2 and will not change significantly with s.

Implications of the scaling law

- Semi-inclusive central production cross sections can show large s dependence. If $\alpha_{sub}(M^2)$ falls with M2, then that subset will fall with s and vice–versa. Central production subsets that fall with s will also exhibit a broader Feynman x distribution.
- Should extend this to se if 4 body scattering (two particle inclusive final state) and higher numbers exhibit similar behavior.
- Can use scaling law to look for resonances. Scaling applies to a continuum of states that populate the cut in M^2 plane. If X is also a resonance in some subset, then interference will occur between signal and background for that mass range and will result in deviations from scaling. This can be used to look for resonances. E.g A1.

Implications of scaling law

- Implies that the pseudo-resonance states x behave as particles, there is fast equilibrium upon scattering. Argues against independent quark fragmentation in DIS. Argues for promoting the state X to have a structure that varies with M^2. This leads naturally to scale breaking.
- I believe that if MIPP can establish this scaling to better than a percent or so in all 36 channels, we have to take these views seriously and alter our theories in accordance.